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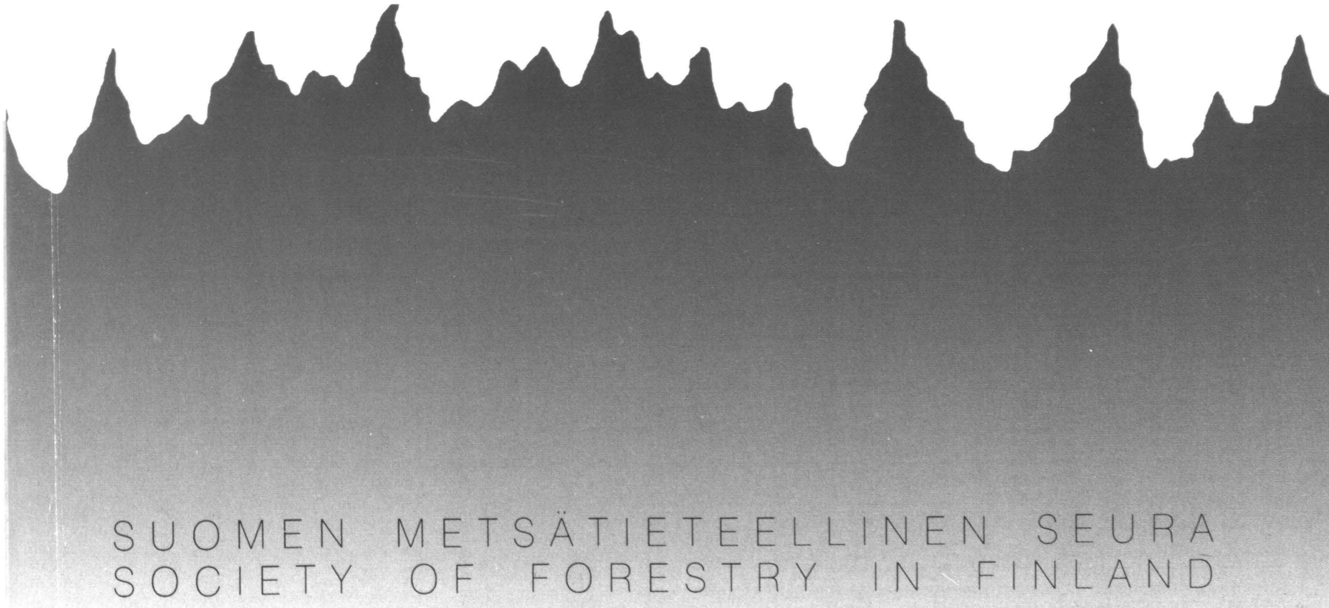

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Variation in water retention characteristics of peat growth media used in tree nurseries

Juha Heiskanen

TIIVISTELMÄ: TAIMITARHOILLA KÄYTETTYJEN KASVUTURPEIDEN VEDENPIDÄTYSTUNNUSTEN VAIHTELU

Heiskanen, J. 1993. Variation in water retention characteristics of peat growth media used in tree nurseries. Tiivistelmä: Taimitarhoilla käytettyjen kasvuturpeiden vedenpidätystunnusten vaihtelu. Silva Fennica 27(2): 77–97.

The water retention characteristics and their variation in tree nurseries and related physical properties were determined for commercially produced growth media made of light, low humified *Sphagnum* peat. A total of 100 samples of peat media were collected from filled seedling trays in the greenhouses of four Finnish nurseries in 1990 before seedlings were grown in the trays. In addition, the physical properties were determined from separate samples for two growth media made of compressed peat sheets and chips. The variation in water retention characteristics in nurseries was described using linear models with fixed and random effects. The sources of variation in the mixed linear models were producer, grade, batch (greenhouse) and sample (tray).

The water retention of the peat media at different matric potentials was comparable to that given in the literature for similar peat media. The media shrank an average of 0–16 % during desorption. The peat grades were finer than the Nordic quality standards for peat growth media. Particles < 1 mm increased and particles 1–5 mm decreased the water retention characteristics measured. The greatest total variation in water retention was at –1 kPa. The water retention of the peat media differed least at –5 and –10 kPa. The water retention characteristics of media from different producers usually differed significantly. The grades, on the other hand, did not differ from each other in their water retention characteristics nor were there significant interactions between producer and grade. The batch (greenhouse) effect was marked but was lower than the effect within batches, where the sample (tray) effect was greater than the effect due to random measurement error. At –10 kPa, the measurement error was, however, clearly greater than the sample effect. The random measurement error was comparable to the batch effect. Aeration of the growth medium is dependent on the water content retained between saturation and –1 kPa. The water availability to seedlings at the nursery phase is affected mainly by water retention between –1 and –10 kPa.

Tutkimuksessa selvitettiin kaupallisesti tuotettujen vaaleiden, vähän maatuneiden rahkaturpeiden vedenpidätyskykyä ja sen vaihtelua metsäpuiden taimitarhoilla sekä muita fysikaalisia ominaisuuksia. Turvenäytteitä kerättiin kaikkiaan 100 kpl neljän eri taimitarhan kasvihuoneista valmiiksi täytetyistä taimiarkeista ennen kasvatuksen aloittamista v. 1990. Lisäksi tutkittiin Vapolevy-turpeen ja ruotsalaisen hiutaleturpeen fysikaalisia ominaisuuksia erillisnäytteistä. Vedenpidätyskyvyn vaihtelua taimitarhoilla kuvattiin käyttäen kiinteiden ja satunnaistekijöiden lineaarisia malleja. Lineaarisissa sekamalleissa vaihtelulähteinä olivat turvetuottaja, karkeusaste, turve-erä (kasvihuoneet) ja näyte (taimiarkit).

Turvekasvualustojen vedenpidätyskyky eri matriisipotentiaalitasoilla oli keskimäärin verrattavissa kirjallisuudessa esitettyyn vastaavantyyppisten kasvuturpeiden vedenpidätyskykyyn. Eri kasvuturpeet kutistuivat desorption aikana keskimäärin 0–16 %. Kasvuturpeiden laatuvaatimuksiin nähden kasvuturpeet olivat karkeusasteeltaan liian heinojakoisia. Hiukkaset < 1 mm lisäsivät ja hiukkaset 1–5 mm vähensivät vedenpidätyskykyä. Vedenpidätyskyvyssä suurin kokonaisvaihtelu oli –1 kPa:ssa. Vähäisimmillään erot eri kasvuturpeiden vedenpidätyskyvyn välillä olivat –5 ja –10 kPa:ssa. Eri tuottajien kasvuturpeiden vedenpidätyskyky poikkesi toisistaan merkitsevästi. Karkeusasteet eivät eronneet vedenpidätyskyvyltään toisistaan eikä merkitseviä tuottajan ja karkeusasteen välisiä yhdysvaikutuksia myöskään esiintynyt. Turve-erien (kasvihuoneiden) välinen vaihtelu oli selvä, mutta vähäisempi kuin erien sisäinen vaihtelu. Erien sisällä näytteen (arkin) vaikutus oli suurempi kuin satunnaisen mittausvirheen vaikutus. Kuitenkin mittausvirheellä oli suurempi vaikutus vedenpidätyskykyyn –10 kPa:ssa kuin näytteellä. Satunnainen mittausvirhe oli suuruudeltaan verrattavissa erävaikutukseen. Kasvualustan ilmanvaihto riippuu ennen kaikkea vedenpidätyskyvystä kyllästystilan ja –1 kPa:n välillä. Taimien veden saatavuuteen vaikuttaa taimitarhavaiheessa vedenpidätyskyky lähinnä –1 ja –10 kPa:n välillä.

Keywords: container grown plants, planting stock, production, density, hydraulic conductivity, porosity, physical properties, substrates.
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Symbols

A	Area of a sample core, mm^2
Db	Bulk density, g cm^{-3}
Dp	Particle density, g cm^{-3}
Dw	Density of water, g cm^{-3}
Fi	Mass of particles in size class i mm in diameter of total mass, % (M M^{-1}), e.g. F1–5 = proportion of particles in class 1 to 5 mm
h	Hydraulic head, i.e. height difference between water levels kept on top of a sample core and below the sample core, mm
Il	Loss on ignition (3h/550 °C), % (M M^{-1})
Ks	Saturated hydraulic conductivity at 10 °C, mm min^{-1}
l	Height of a sample core, mm
Mi	Total mass of sample at –i kPa matric potential, g e.g. M1 = total mass at –1 kPa
Ms	Mass of solids i.e. dry mass (24h/105 °C), g
Q	Water volume, mm^3
t	Time interval during which water volume Q has flowed through a sample core, min
Vf	Total porosity, % (V V^{-1})
Vi	Sample volume in % at –i kPa in relation to volume at –0.1 kPa, e.g. V1 = relative volume at –1 kPa
θi	Water retained of total volume at –i kPa matric potential, % (V V^{-1}), e.g. θ1 = water content at –1 kPa, θ1–10 = water content difference between –1 and –10 kPa

1 Introduction

The material used most widely in the Nordic countries as growth medium in container seedling production is light, low humified peat consisting of *Sphagnum* sp. mosses. Material for the manufacture of peat growth medium is harvested from peat bogs and transported to a factory where it is stored in stacks before processing. Sieved and graded peat growth medium is compressed into bales and then delivered to nurseries. Into most peat growth media fertilizers are also incorporated. In the nurseries the peat is finally unpacked and emptied into a filling machine, which loosens, fills and compresses peat into the containers of seedling trays.

In nurseries, the growth of tree seedlings is greatly affected by the availability of water and oxygen to the roots from the growth medium. Water and oxygen availability are determined, in addition to external growth conditions, also by the water retention characteristics of the growth medium, which are strongly dependent on pore size distribution (Hillel 1982). The pore size distribution of the soil is, in turn, affected by particle size distribution, degree of compactness and structure (Hillel 1971,1982, Currie 1984).

In the case of light, low humified (H1–3, von Post scale) peat growth media, the physical properties are determined primarily by the composition of plant species making up the peat and secondarily by particle size distribution (Puustjärvi 1973). The peat growth media used in tree nurseries are usually graded as fine, medium or coarse, as defined by Nordic standards (Puustjärvi 1982a). According to the regulations of the Finnish Ministry of Agriculture and Forestry, the first class light, low humified (H1–3) cultivation peat, which is the peat used in tree nurseries, should contain at least 90 % remains of *Sphagnum* mosses, from which over 80 % should belong to the Acutifolia group. Less than 3 % shrubs and wood remnants and less than 6 % cotton-grass remnants are allowed in the dry mass of the peat (Maa- ja... 1986). The composition of the plant remains affects the surface properties of peat, which, in addition to pore size distribution, have a great effect on water retention characteristics and wettability (Päivänen 1973, Puustjärvi 1973). The surface properties of dry organic materials may even cause water repellency and nonwettability (Hillel 1971, Puustjärvi 1973).

Variation in the physical properties of peat media causes a corresponding change in their water retention characteristics. This may further induce variation in the availability of water and air to the seedlings. Great variation in the water and aeration characteristics of a peat batch may thus cause uneven plant growth within the crop (Puustjärvi 1973, 1975a). In general, the water retention characteristics of peat differ according to bulk density, which changes mainly with the degree of humification (Päivänen 1969, 1973, Puustjärvi 1970). The water retention characteristics of low humified peat growth media are, however, mainly determined either as averages within different peat grades only (e.g. Puustjärvi 1973, Verdonck et al. 1983) or by describing them in terms of few and rather imprecise variables, such as water and air capacity (e.g. Puustjärvi 1969, Folk et al. 1992). Little is therefore known about the actual variation in the water retention characteristics of peat growth media under real growing conditions.

In tree nurseries, a greenhouse or part of a greenhouse is the smallest unit in which irrigation and fertilization can usually be adjusted. The amounts of water and timing of irrigation are usually adjusted by visual and tactile evaluation or by weighing seedling trays and then determining their mass deficit with respect to the mass of a tray in which the target water content is considered to prevail. The availability of water to an individual seedling, however, depends on the actual water and aeration conditions in a container which may differ from the average conditions in the tray. In order to achieve even seedling growth and quality within a crop, irrigation and other growing conditions in greenhouses must be monitored and manipulated effectively. To facilitate these management practices, information is needed about the actual variation in water retention characteristics of different peat products in seedling trays within and between greenhouses. In addition, the manufacture and formulation of peat growth media and mixtures require information on variations in peat properties and the causes of these variations.

The aim of this study was to determine the water retention characteristics and related physical properties of light, low humified peat growth media used in growing container seedlings at tree nurseries and, in particular, the variation in the water retention characteristics of these peat media. Some implications of the determined characteristics for the growth of seedlings and irrigation are further discussed. The differences in water retention characteristics between different peat products and their variation in nurseries were analyzed using linear models with fixed and random effects.

2 Materials and methods

2.1 Peat media

The peat growth media studied here were light, low humified *Sphagnum* peat. The peat grades collected were the coarse and medium grades of two Finnish producers, which account for the major part of the peat medium production in Finland (Vapo and Kekkilä Corp.). The peat grades, specified by the producers, refer to Nordic standards (Puustjärvi 1982a). The peat products of the Vapo Corp. were D1K2 and E1K2 and those of the Kekkilä Corp. ST-400 M6 and PP6 for coarse and medium grades, respectively. Peat was collected from newly filled seedling trays at four tree nurseries (Joroinen, Puupelto, Suonenjoki, Syrjälä) in spring 1990. The peat of a tray was fully emptied onto the ground, from which a gently mixed sample of about 3 dm^3 was placed in a plastic bag. Thus the water content of the peat samples was almost the same as that in the packages delivered from the producers (see Heiskanen 1990). The trays were type TA made of polystyrene (Lännen Corp., Finland).

Each peat sample was collected from a separate, randomly selected seedling tray. The trays had been randomized using random number tables to select the ordinal numbers of the columns and rows of trays in a greenhouse. For each of the 4 producer and grade combinations, 5 groups of 5 randomly selected samples were collected, each from a separate, randomly selected greenhouse. Each group of 5 samples from a greenhouse therefore represented a batch of peat. Peat batches from the same producers were assumed to represent time variable peat batches from the whole production lot of a year. The lots are not expected to vary more between different years than the batches vary within years.

In addition, 10 samples of compressed sheet peat (Vapo Corp.) produced for the Vapo container growing method and 10 samples of Swedish chip peat (Hasselfors Corp.) were randomly collected from a production batch (1–2 packages). The total number of samples studied was thus 120 ($2 \cdot 2 \cdot 5 \cdot 5 + 10 + 10$). Before laboratory determinations, the samples were stored a maximum of 9 months in cold storage (5–10 °C).

2.2 Laboratory determinations

The particle size distribution of each sample of peat medium was determined by dry sieving through standard sieves of 20, 10, 5 and 1 mm hole size (Puustjärvi 1973, Wilson 1983, Kurki 1985). For each main sample collected, a loose, air dried sample of 300 cm^3 was sieved for 2 minutes using a mechanical sieving machine (Retsch Corp., Germany). In order to sieve the sheet peat, it was first moistened and loosened by hand and then air dried.

Loss on ignition, which provides an approximate estimate of organic matter content, was determined by igniting a sample of about 2 g at 550 °C for 3 hours. Particle density was measured using liquid pycnometers with water as the filling liquid and a water bath (Heiskanen 1992). Bulk density was determined as the ratio of dry mass (dried at 105 °C) to saturated volume (volume determinations described later). Total porosity (%) was calculated from particle and bulk densities using Formula 1.

$$Vf = ((Dp - Db) / Dp) \cdot 100. \qquad (1)$$

Saturated hydraulic conductivity was measured by applying the constant head percolation method (Dirksen and Klute 1986, Kretzschmar 1989). Samples were filled into 195 cm^3 cylindrical containers that were 63 mm in height. The top end of the cylinder was open and the base was perforated throughout with 1 mm holes. The samples were compressed from above for 5 seconds with a pressure of 10 g cm^{-2} (Heiskanen 1990) and were then allowed to become saturated in free water for a day. A similar empty cylinder in which the water table was kept constant was then placed tightly on top of the sample cylinder. Before the actual measurement of percolation, tap water was first allowed to percolate through the cylinders overnight. The amount of water that had passed through the sample was then weighed at 30 min intervals. When the water flow had stabilized to almost constant (within a day), this final rate of flow was recorded (see Päivänen 1973). The value of saturated hydraulic conductivity (Ks) was calculated using Formula 2, which is based on the principle of Darcy's law ($l = 63$ mm, $A = 3117$ mm^2, $h = 80–95$ mm).

$$Ks = (Q \cdot l) / (A \cdot h \cdot t). \qquad (2)$$

Because the temperature of the water that flowed through the samples was found to vary between 8 and 18 °C, the effect of varying viscosity on hydraulic conductivity was taken into account by using correction coefficients (Sillanpää 1956, Campbell 1985). The coefficients were determined as the ratio of kinematic viscosity at the observed temperature to that at 10 °C. The corrected values for saturated hydraulic conductivity were considered to estimate the runoff rate of excessive water occurring in seedling containers during cool fall rains on the hardening fields in tree nurseries.

For measurements of bulk density and water retention, peat samples were filled loosely into 250 cm^3 open ended metal cube containers (63 × 63 × 63 mm). The bottoms of the cubes were first sealed with polypropylene netting containg holes 1 mm in diameter. The samples were compressed in the same way as the cylinder samples in the determination of saturated hydraulic conductivity and were then allowed to become saturated for two days in free water, the level of which was kept just below the midlevel of the cubes. To ensure complete saturation, additional water was also sprayed from above occasionally. After saturation, the samples were weighed and their volume was measured with a ruler to a precision of 0.5 mm. This mass was considered to correspond to water retention at the matric potential of –0.1 kPa. The measured volume was used to calculate bulk density.

Water retention characteristics were measured after saturation of the cube samples using a pressure plate apparatus (Soil Moisture Equipment Corp., USA). Matric potentials of –1, –5, –10, –50 and –100 kPa were applied successively over the cube samples until water had ceased flowing from the pressure chambers (about 2 weeks). After rewatering, the same samples were used in all successive applications of decreasing matric potential (Heiskanen 1990). After each matric potential application, samples were weighed and their volume was determined by measuring shrinkage in vertical and horizontal directions with a ruler to a precision of 0.5 mm. The shrinkage of the samples at the applied matric potentials was determined as relative volume to volume at –0.1 kPa. After the masses and volumes of samples at –100 kPa had been determined, the samples were dried at 105 °C until they reached constant mass (24 h), and their dry masses were then weighed.

At –1500 kPa, water retention was measured separately from parallel samples that had been saturated and filled into plastic rings ($d = 50$ mm, $h = 10$ mm). Shallow sample rings were used to ensure contact between the ceramic disk and the samples as well as faster cessation of the slow water flow from the samples. Shrinkage could not be measured. Volumetric water retention (%) at each matric potential was determined using Formula 3 (e.g. Hillel 1971), which gives values in relation to the saturated peat volume (≈ container volume). If needed, water retention can be transformed to a transient peat volume basis at different matric potentials by dividing water retention with the shrunk peat volume (as a proportion of the saturated volume).

$$\theta i = (((Mi - Ms) / Dw) / (Ms/Db)) \cdot 100. \qquad (3)$$

In order to estimate the tray (sample) effect within batches (greenhouses), the random measurement error was estimated using separate data. These data were collected by subsampling main samples randomly from each producer and grade combination (sheet and chip peat excluded). Each combination of subsamples consisted of 6 to 10 samples. Every different combination was collected for each 3 final matric potential level (–1, –10, –100 kPa) to be measured. The samples were handled and measured as described earlier for the main material until the last matric potential to be applied. Then the samples were measured twice after the two successive applications of the last matric potential. The difference between the two measurement values could then be determined. To save time in the laboratory determinations, the subsampling and reduced number of measured matric potentials were used.

2.3 Statistical methods

2.3.1 Estimation of the effects of sources of variation

Variation in the water retention characteristics was analyzed using mixed linear models (Searle 1971, Sokal and Rohlf 1981). The water retention characteristics of peat growth media were assumed to differ according to producers, sieving grades, production batches and individual trays. The effect of the producer is due to peat bogs used for harvesting as well as to all handling and storage specific for a given producer before sieving and packing of the peat. The grade effect is due to the sieving method. The batch effect appears in peat variations between greenhouses in nurseries and is due to differences within production fields and peat storage stacks as well as to differences in handling of peat during production and filling into seedling trays. The tray effect includes variation in peat between trays within batches (greenhouses).

In mixed linear models in general, the effects of specific classes or treatments are regarded as fixed effects. Random effects, on the other hand, are assumed to be random samples from the population of the variable (Searle 1971, Sokal and Rohlf 1981). Therefore, the effects of producer and grade were considered to be fixed and those of batch and tray random. Differences in grades and sieving methods of different producers were estimated using the producer and grade interaction. The effects of batch and tray were nested hierarchically within the higher effects. Tray effect was included into residual effect, which was also expected to include measurement errors. The total variation in an individual tray was thus described using mixed linear Model 4.

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{ij} + d_{(ij)k} + e_{(ijk)l}, \qquad (4)$$

where
y_{ijkl} = value in an individual tray,
μ = general mean,
α_i = producer effect, (i = 1 Vapo, i = 2 Kekkilä)
β_j = grade effect (j = 1 coarse, j = 2 medium),
γ_{ij} = interaction between producer and grade,
$d_{(ij)k}$ = random batch effect within grade and producer, $E(d_{(ij)k}) = 0$, $var(d_{(ij)k}) = \sigma^2_d$,
$e_{(ijk)l}$ = random residual effect within batch, grade and producer, $E(e_{(ijk)l}) = 0$, $var(e_{(ijk)l}) = \sigma^2_e$, $cov(d_{(ij)k}, e_{(ijk)l}) = 0$.

Variation in the results for measurement of water retention characteristics was increased by random and systematic measurement errors. Systematic errors, however, could not be estimated and were assumed to be negligible. The random measurement errors were included into the residual effect $e_{(ijk)l}$ of Model 4. Hence, in order to estimate the actual tray effect within batches, the random measurement errors should first be estimated and then subtracted from the residual effect. The effect of random measurement error was estimated using the following procedure.

Any value y_1 of a first water retention measurement at a matric potential level was assumed to include a true value z_1 and a random measurement error e_{m1}, i.e. $y_1 = z_1 + e_{m1}$. The second successive value for measurement of the same sample at the same matric potential was expressed correspondingly: $y_2 = z_1 + \delta + e_{m2}$, where δ is an assumed difference between the successive measurement values due to structural changes in the medium during the second application of matric potential and measurement. e_{m1} and e_{m2} were assumed to be uncorrelated and to have equal variances. Therefore, the difference D between the two successive measurements was described by Equation 5.

$$D = y_2 - y_1 = \delta + (e_{m2} - e_{m1}), \qquad (5)$$

where
$E(e_{m2} - e_{m1}) = 0$, $cov(e_{m1}, e_{m2}) = 0$,
$var(e_{m2} - e_{m1}) = var(e_{m1}) + var(e_{m2}) = 2var(e_m)$
$= 2\sigma^2_{em}$.

Structural changes during the second successive measurement were expected to be dependent on the same variation sources as the water retention. Thus, the values of δ depended on producer, grade, batch and tray. Therefore, δ was expressed by Model 6.

$$\delta_{ijkl} = \mu' + \alpha'_i + \beta'_j + \gamma'_{ij} + d'_{(ij)k} + e'_{(ijk)l}, \qquad (6)$$

where the accented letters indicate the same effects as those in the Model 4, $var(e') = \sigma^2_{e'}$.

By combining Models 5 and 6, D was expressed further by Model 7.

$$D_{ijkl} = \mu' + \alpha'_i + \beta'_j + \gamma'_{ijj} + d'_{(ij)k} + \varepsilon_{(ijk)l}, \qquad (7)$$

where
$\varepsilon_{(ijk)l} = e'_{(ijk)l} + e_{m(ijk)l2} - e_{m(ijk)l1}$,
$var(\varepsilon) = \sigma^2_\varepsilon = \sigma^2_{e'} + 2\sigma^2_{em}$.

Variance $var(\varepsilon)$ was estimated by computing Model 7 with the separate data for measurement error. $Var(e')$ was considered = 0, when an estimate for the variance of random measurement error was obtained from the equation $var(e_m) = var(\varepsilon)/2$. The procedure used yielded an estimate (giving on average overvalues) for the random measurement error in which the effects due to variations in peat material were excluded as far as possible.

General Model 4, which contained the main data, previously yielded the variance of the residual effect within batches var(e), which was the sum of the variances of random measurement error, $var(e_m)$, and the effect of trays within batches, $var(e_s)$. Thus, an estimate (giving on average undervalues) of the variation due to trays within batches was determined from Equation 8.

$$var(e_s) = var(e) - var(\varepsilon)/2. \qquad (8)$$

2.3.2 Data analysis

One way analysis of variance and Tukey's test were applied to evaluate the differences between the compared group means. Group means and standard deviations of the variables were calculated for each producer and grade combination from batch means (i.e. trays combined within greenhouses). Batch means were used as independent observations, because trays were dependent on each other within batches (see Model 4). Levene's test was used to test the homogeneity of variances. The F-test and Tukey's pairwise comparisons were also used when variances were unequal, because the obtained significance values were close to those achieved with the Brown-Forsythe test, which does not have the requirement of equal variances.

Mixed effect linear models were used in order to analyze further the sources of variation for the water retention characteristics of the conventionally graded peat media in nurseries (sheet and chip peat excluded). In order to express the effects on the same scale and units as the variables used, the fixed effects were presented as deviations from the general mean and the random effects as standard deviations.

Correlation coefficients were calculated to assess linear relationships between variables (n = 20). Stepwise regression analysis was also used to find the best predicting regression equations for the independent variables. Data were analyzed using BMDP-software (7D, 1R, 2R, 3V, 8V) (BMDP... 1990).

3 Results

3.1 Physical properties of peat media

All the peat media studied were made up mainly of particles in size classes < 1 and 1–5 mm (Table 1). The amount of particles > 20 mm was negligible. The amount of particles 10–20 mm was also scant. Some of the particles > 1 mm were found to be aggregates, most of which were in the class 1–5 mm. In terms of particle size distribution, the grades of Producer 1 (Vapo Corp.) deviated from each other only slightly. The grades of Producer 2 (Kekkilä Corp.) had a more marked difference in particle size distribution. The medium grade contained, on an average, more particles < 1 mm than the coarse grade did. Because they contained more particles < 1 mm, both grades of Producer 1 were clearly finer than those of Producer 2. The grades of Producer 2 also contained, on average, slightly more particles 1–5 mm. For particles < 5 mm, however, the standard deviations of Producer 2 were as much as 4 times greater than those of Producer 1. The sheet peat clearly had the least amount of particles < 1 mm.

The particle density of the peat media did not differ from each other significantly (Table 2). However, the particle density was consistent within both producers of the conventionally graded peat (sheet and chip peat excluded). Particle density tended to increase as the amount of particles 5–10 mm increased (Appendix 1). Bulk density was also relatively consistent within producers (Table 2). The bulk density of chip peat was significantly lower than that of the other peat media. The greater the amount of particles < 1 mm or the less particles 1–5 mm, the greater was the bulk density (Appendix 1). Bulk density was not, however, significantly related to particle density.

Loss on ignition varied only slightly (Table 2).

Table 1. Means and standard deviations (%, M M^{-1}) for particle size (mm) of the peat media calculated from means of five peat batches. Data for sheet and chip peat were calculated from six samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	F < 1	F1–5	F5–10	F10–20	F > 20
Coarse1	62.5±3.4a	28.3±4.7ab	6.7±1.3a	2.2±1.7ab	0.2±0.4a
Medium1	62.6±3.5a	24.3±1.3a	10.0±1.3ab	2.8±2.6ab	0.4±0.6a
Coarse2	38.7±12.2b	44.5±13.0bc	11.2±0.6ab	5.2±1.8a	0.4±1.0a
Medium2	51.8±13.1ab	35.5±13.4abc	10.5±2.1ab	2.2±1.0ab	0.0±0.0a
Sheet	24.0±4.4c	51.8±14.9c	21.2±16.3b	2.9±2.9ab	0.2±0.2a
Chip	38.7±2.3b	52.7±2.6c	8.6±1.2ab	0.0±0.0b	0.0±0.0a
p	< 0.00005	0.0001	0.036	0.009	0.545

Table 2. Means and standard deviations for particle (Dp) and bulk (Db) densities, loss on ignition (Il) and saturated hydraulic conductivity (Ks) of the peat media calculated from means of five peat batches. Data for sheet and chip peat were calculated from six samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	Dp, g cm^{-3}	Db, g cm^{-3}	Il, % M M^{-1}	Ks, mm min^{-1}
Coarse1	1.63±0.03a	0.087±0.005a	94.4±0.3a	0.9±0.4a
Medium1	1.63±0.03a	0.080±0.005ab	95.3±0.6ac	3.1±1.2b
Coarse2	1.67±0.02a	0.072±0.001b	95.6±0.6ac	1.2±0.6ab
Medium2	1.67±0.04a	0.073±0.009b	93.1±0.8b	1.5±0.4ab
Sheet	1.60±0.05a	0.085±0.005a	95.6±0.4c	2.5±1.6ab
Chip	1.66±0.04a	0.057±0.005c	95.4±0.8ac	5.2±1.4c
p	0.052	< 0.00005	< 0.00005	< 0.00005

The lowest loss on ignition was found in the medium grade peat of Producer 2. The loss on ignition (hence also the ash content) was not clearly dependent on particle size or on particle and bulk densities (Appendix 1). Compared to the other variables, saturated hydraulic conductivity had relatively large standard deviations with respect to the means (Table 2). Saturated hydraulic conductivity was significantly higher for chip peat than for the other peat media. There was also a significant difference between the grades of Producer 1. The hydraulic conductivity tended to increase with the water retention at –0.1 to –100 kPa; but it was not highly correlated with particle size distribution or particle and bulk densities (Appendix 1).

The total porosity of the peat media varied relatively little (Table 3, Fig. 1). However, the total porosity of chip peat was clearly the greatest. The highest average water retention at –0.1 kPa matric potential was found in the peat of Producer 1. The sheet peat had significantly the lowest water retention, despite the fact that its standard deviation was the greatest. At –1 kPa matric potential, the peat of Producer 1 continued to retain more water than that of Producer 2. Again, the sheet peat retained the least amount of water. Furthermore, the water retention of the chip peat was further at about the same level as the peat of Producer 2. At –1 kPa, the standard deviations for water retention were relatively large compared to those at the other matric potentials measured.

At –5 kPa, the differences in water retention characteristics between the peat media decreased (Table 3, Fig. 1), and only the sheet and chip peat differed significantly from each other. At –10 kPa, the water retention of all the peat media was very similar and did not differ significantly between media. At –50 kPa, the differences were again greater. The sheet peat retained significantly greater amount of water than the other media did. The peat of Producer 1 with the chip peat retained, on average, more water than the peat of Producer 2. The water retention of each medium at –100 kPa was only slightly lower than at –50 kPa. At –1500 kPa, the chip peat retained the least water. The sheet peat retained, on average, the most water. No significant differences existed between the conventionally graded peat media.

Table 3. Means and standard deviations for total porosity (%) and water retention characteristics (%) of the peat media calculated from means of five peat batches. Data for sheet and chip peat were calculated from ten samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	Vf	θ0.1	θ1	θ5	θ10	θ50	θ100	θ1500
Coarse1	94.6±0.4a	91.2±2.2ab	70.3±5.9a	36.9±1.9ab	30.6±1.2a	24.5±0.8ac	24.1±0.9ac	16.4±1.7ab
Medium1	95.1±0.3ab	93.0±1.2a	71.7±3.0a	36.6±1.0ab	31.1±1.0a	25.5±1.0a	24.7±1.0a	14.3±0.5a
Coarse2	95.6±0.1bc	86.8±2.7b	63.3±6.9ac	36.3±3.0ab	29.9±2.5a	20.0±0.9b	19.3±0.8b	13.4±0.5a
Medium2	95.7±0.4c	89.9±2.3ab	63.6±3.5ac	36.2±2.5ab	30.6±1.7a	21.2±2.0bc	20.7±2.2bc	14.6±2.6a
Sheet	94.9±0.3a	78.8±5.2c	42.0±2.6b	34.2±2.2a	31.2±1.7a	29.1±2.6d	27.7±2.1d	18.0±2.7b
Chip	96.7±0.2d	89.6±1.7ab	58.5±9.4c	38.9±2.9b	32.4±2.7a	22.7±2.7b	21.1±2.0b	7.8±0.5c
p	< 0.00005	< 0.00005	< 0.00005	0.007	0.275	< 0.00005	< 0.00005	< 0.00005

The amount of water released at –1 kPa matric potential with respect to full saturation (θVf–1) was, on average, lower in the peat of Producer 1 than in that of Producer 2, although the differences were not significant (Table 4). Sheet and chip peat clearly had greater water release, which also differed significantly from the peat of Producer 1. The water retention in the range –1 to –10 kPa (θ1–10) was now greatest in the peat of Producer 1. It did not, however, differ significantly from the peat of Producer 2, but from the sheet and chip peat, which clearly retained the least water. The water retention between –10 and –50 kPa (θ10–50) was markedly lower than in the previous ranges. In this range, the peat of Producer 1 had significantly lower water retention than that of Producer 2. The sheet peat retained water only slightly. In the lowest matric potential range (–50 to –1500 kPa), the water retention was comparable to θ10–50 and the peat of Producer 2 had the lowest average water retention.

The volume of the peat media at desorption was, on average, 0–16 % smaller than at saturation (Table 5). The sheet and chip peat usually shrank significantly less than the conventional peat grades did. After application of the –1 kPa

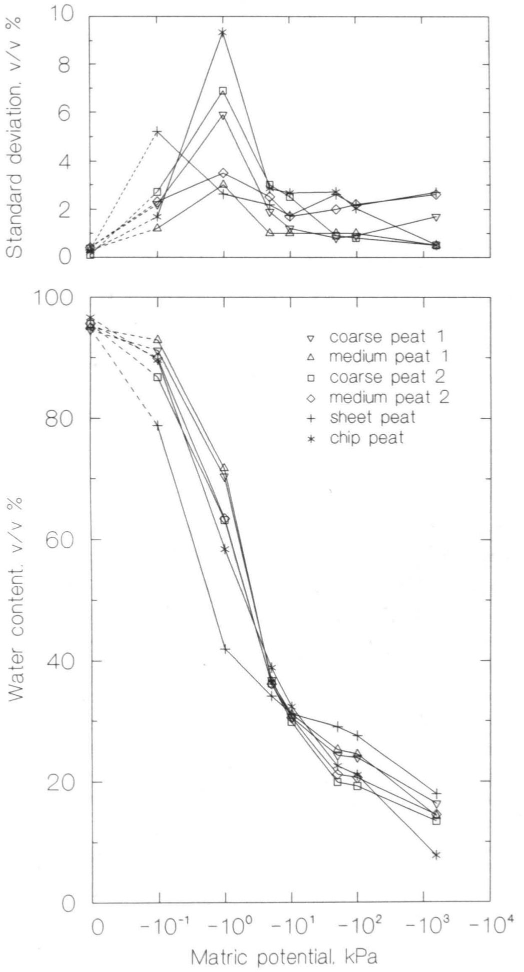

Fig. 1. Mean water retentions and their standard deviations in the peat growth media at different matric potentials at desorption (from Table 3).

Table 4. Means and standard deviations for water retention characteristics (%) of the peat media within selected matric potential ranges calculated from means of five peat batches. Data for sheet and chip peat were calculated from ten samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	Vf–1	θ1–10	θ10–50	θ50–1500
Coarse1	24.3±5.6a	39.7±5.1a	6.2±0.7a	8.1±1.7ab
Medium1	23.3±3.0a	40.6±3.3a	5.7±0.3a	11.2±1.3ac
Coarse2	32.3±7.0ac	33.4±5.5ac	9.9±1.7b	6.5±0.8b
Medium2	32.1±3.7ac	33.0±2.3ac	9.3±1.0b	6.7±0.7b
Sheet	54.0±2.6b	10.9±1.7b	2.1±1.4c	11.1±2.6ac
Chip	43.4±10.4bc	26.1±7.1c	9.7±1.8b	14.3±2.7c
p	< 0.00005	< 0.00005	< 0.00005	< 0.00005

Table 5. Mean shrinkages (%) of the peat media at desorption expressed as relative volumes to volume at –0.1 kPa (= 100%). Values are means and standard deviations calculated from means of five peat batches. Data for sheet and chip peat were calculated from ten samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	V1	V5	V10	V50	V100
Coarse1	88.2±3.9a	88.6±1.3a	90.1±2.3a	88.2±2.6ac	86.4±1.6ab
Medium1	88.9±2.0a	90.4±1.4a	91.9±1.5ac	89.5±2.1ac	89.7±0.9a
Coarse2	85.8±1.2a	86.7±2.8a	87.0±2.7a	84.9±1.3a	83.5±2.6b
Medium2	86.1±3.3a	88.6±4.6a	87.7±4.5a	86.8±4.6a	86.4±3.5ab
Sheet	98.6±3.4b	97.7±3.3b	99.1±3.5b	98.9±7.1b	99.8±3.5c
Chip	95.4±2.1b	95.1±2.1b	95.4±2.0bc	95.0±2.1bc	95.0±2.5d
p	< 0.00005	< 0.00005	< 0.00005	< 0.00005	< 0.00005

Table 6. Stepwise calculated regression equations, root mean square errors (RMSE) and adjusted coefficients of determination (R^2) describing the relationships between water retention charcateristics and other physical peat properties. Batch means were used as independent observations (n = 20).

Variable	Equation	RMSE	R^2
θ0.1	82.62 + 0.1411 (F < 1)	2.47	0.34
θ1	76.14 – 0.5806 (F1–5)	5.37	0.23
θ5	59.40 – 0.2239 (F < 1) – 0.3266 (F1–5)	1.68	0.35
θ10	33.05 – 0.084 (F1–5) + 1.059 (F> 20)	1.19	0.46
θ50	7.03 – 0.1059 (F < 1) + 128.74 (Db)	1.43	0.70
θ100	5.52 – 0.0989 (F < 1) + 145.43 (Db)	1.41	0.71
θ1500	50.99 + 166.64 (Db) – 0.5213 (Il)	1.03	0.68
θVf–1	18.25 + 0.2943 (F1–5)	5.45	0.26
θ1–10	42.84 – 0.1854 (F1–5)	4.95	0.13
θ10–50	–275.43 + 2.9611 (Vf) + 0.3766 (F10–20)	1.31	0.64
θ50–1500	–78.35 + 0.0821 (F < 1) + 0.8671 (Il)	1.82	0.32
Ks	–7.99 – 0.0061 (F1–5) + 0.0877 (Vf)	0.096	0.21

matric potential, the peat volume did not alter greatly during further desorption. The more water was retained, the less was the measured shrinkage in the conventional peat grades (Appendix 1). The more particles < 1 mm or the less particles 1–5 mm there were, the less was the shrinkage.

In general, the greater the amount of particles < 1 mm, the greater was also the water retention at different matric potentials (Appendix 1). The water retention decreased with the amount of 1–5 mm particles. The total porosity decreased with particles < 1 mm and increased with particles 1–5 and 5–10 mm. The air space at –1 kPa (θVf–1) and the amount of water retained between –10 and –50 kPa matric potentials also decreased when the amount of particles < 1 mm increased. Particles 1–5 mm had the opposite effect. Retained water in the matric potential ranges –1 to –10 kPa and –50 to –1500 kPa increased when particles < 1 mm increased or particles 1–5 mm decreased. The increase in loss on ignition (i.e. decrease in ash content) tended to decrease the water retention at –1500 kPa (Appendix 1).

The water retention characteristics could be predicted fairly well from the used physical properties of peat, since the root mean square errors (standard errors of the estimates) of the multiple regression equations were relatively low (Table 6). However, the water retention could be predicted less accurately at high matric potentials than that at lower matric potentials. At high matric potentials, the fine particle size fractions (< 5 mm) predicted best. With decreasing matric potentials, bulk density became more important. Loss on ignition was also a significant factor in predicting water retention at –1500 kPa. The water contents retained within the selected matric potential ranges were more poorly predictable than at the individual potentials. The root mean square errors with respect to the means were over ten times higher than those at the single matric potentials.

3.2 Effects of sources of variation on water retention characteristics

The greatest effect on the water retention characteristics was, in general, the residual effect (variation within batches) (Figs. 2, 3, Appendices 2, 3). At –50 and –100 kPa, the deviation from the general mean due to producer was, however, even greater than the standard deviation of the residual effect. Water retention differed statistically significantly ($p < 0.05$) between producers. The producers did not, however, differ significantly from each other at –5, –10 and –1500 kPa (see also Fig. 1). The grades were also not statistically different nor were there interactions between producer and grade. The batch effect was, however, relatively large at matric potentials between –5 and –1500 kPa. At matric potentials > –5 kPa, the batch effect was relatively less. The greatest variation in water retention was at –1 kPa (see also Table 3, Fig. 1) to which the residual effect contributed most.

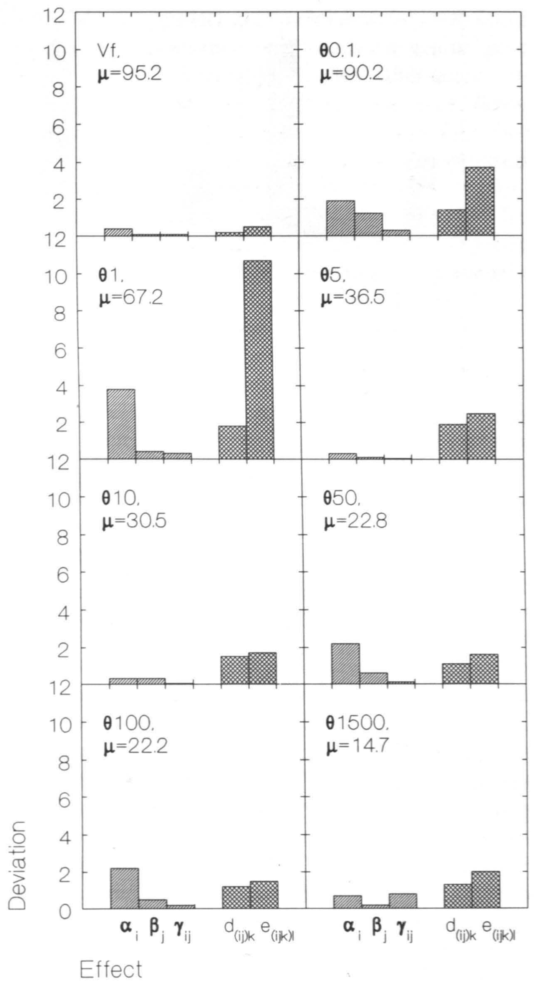

Fig. 2. General means (μ), fixed effects (as absolute values for deviations from the general mean) and random effects (as standard deviations) of water retention characteristics (from Model 4).

Within all the selected matric potential ranges,

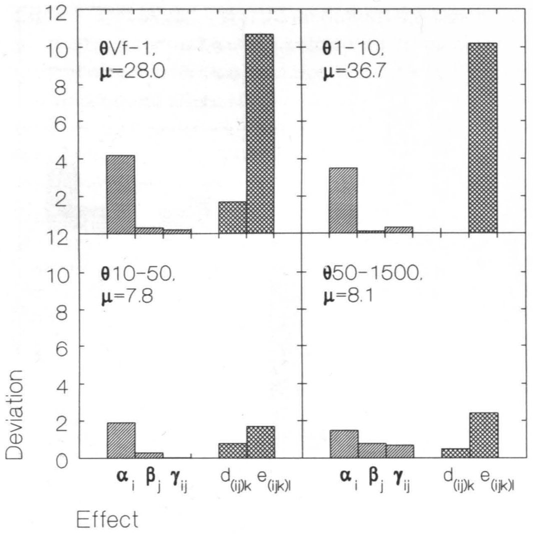

Fig. 3. General means (μ), fixed effects (as absolute values for deviations from the general mean) and random effects (as standard deviations) of water retention characteristics within selected matric potential ranges (from Model 4).

the water retention differed significantly between producers (Fig. 3, Appendix 3). It also differed between grades but only in 50–1500, at which range an interaction also existed between producer and grade. The batch effect was rather small compared with the residual effect.

The residual variation (variation within batches) made up the greatest part of the total variation in water retention at –1 kPa (Figs. 2, 3, Appendices 2, 3). The tray effect within batches was markedly higher than the random measurement error (Table 7), which accounted for a slightly higher effect on the total variation than the batch effect did (Fig 2). At –10 kPa, the greatest source of variation was also the residual effect. However, the measurement error clearly had a greater effect on variation within batches than the tray effect did (Table 7). The measurement error had about as great effect on the total variation as the batch did (Fig. 2). At –100 kPa, the residual variation was relatively less than at –1 and –10 kPa, but was still clear. The greater source of variation within batches was again the tray effect (Table 7). The effect of measurement error was clearly lower than that of batch (Fig. 2). The decrease in the average difference between successive measurements at –1 to –100 kPa indicates that the peat structure was compacted, which caused the amount of retained water to increase during the second measurement (Table 7).

Table 7. Means (μ), mean differences of two successive measurements (diff, % units) and standard deviations (Sd) of measurement error (e_m), tray effect (e_s) and total effect within batches (e) of selected water retention characteristics (from Model 8).

Variable	μ	diff	Sd (e_m)	Sd (e_s)	Sd (e)
θ1	67.2	3.0	2.4	10.4	10.7
θ10	30.5	0.3	1.6	0.6	1.7
θ100	22.2	–0.7	0.6	1.4	1.5

4 Discussion

4.1 Physical properties of peat media

All grades of conventional peat media analyzed in this study were finer than defined by Nordic standards (Puustjärvi 1982a). This may be because the particles comminuted or deaggregated after sieving or because of inappropriate sieving methods used by the producers. Only the sheet peat contained less than 30 % particles < 1 mm and hence only it can be considered coarse. The coarse peat of Producer 2 and the chip peat were medium grade. The rest of the peat media were fine grade since they had less than 70 % but more than 40 % particles < 1 mm. The sheet and chip peat media were coarser than the conventional peat grades. This likely was partly due to the fact that these peat media were taken into the study from packages without comminution or deaggregation with handling at nurseries. In addition, the sheet peat material indeed consisted of rather coarse fibres of cotton-grass and *Sphagnum* mosses and the chip peat consisted of compressed peat aggregates. It is likely that these peat materials do not so easily tend to become finer after manufacture. The sheet peat can be considered to be the coarsest, since it had more particles in size class 5–10 mm than the other media did.

The rather consistent particle density of each producer indicates that the peat material of a given producer had relatively similar density of plant remains due to the specific particle size fractions or moss composition of the bogs from which the peat was harvested. The particle density of the peat media was comparable to the values presented in the literature (Puustjärvi 1969, Heiskanen 1992). The particle density of natural bog peat has been reported to be slightly lower (Päivänen 1973) than that of the peat growth media. The premix-fertilization probably increased the particle density of the peat media. The ashless particle density calculated for the peat growth media was about 1.55 g cm^{-3} (see Heiskanen 1992). The bulk density was comparable to that given in the literature for light peat (Puustjärvi 1969, Päivänen 1969,1973, Verdonck et al. 1983, Heiskanen 1990). The loss on ignition was somewhat lower than that reported for natural *Sphagnum* peat (Päivänen 1969, 1973). The ash content of the media was probably also increased by fertilizers.

The saturated hydraulic conductivity of the peat media studied was comparable to values reported by Puustjärvi (1982c). The values reported by Korpijaakko and Radforth (1972) and Päivänen (1973) for natural *Sphagnum* peat (H1–3) were also consistent with the present results. However, the quoted results have been determined at higher temperature (≥ 15 °C). The values for saturated hydraulic conductivity may be very close to those for unsaturated (at –4 kPa) hydraulic conductivity (Heiskanen 1993b). At persistent full saturation, the low hydraulic conductivity may be due to low permeability of the pores, because the peat colloids have probably swollen more and hence blocked more of the pores than at desorption just after transient saturation.

The values for total porosity of the peat growth media agreed with values presented in the literature (e.g. Puustjärvi 1969,1973, Verdonck et al. 1983). The sheet and chip peat were coarser than the other media and they thus had clearly greater air filled porosity at –1 kPa. In addition, the lower shrinkage of the sheet and chip peat compared with the other peat media probably contributed to their differing water retention. The water retention of the conventionally graded peat media was comparable to that of similarly compressed and graded peat (Heiskanen 1990) and to that of uncompressed, medium grade peat (Puustjärvi 1973) (Table 8). The water retention of uncompressed, coarse grade peat was, however, lower, which was caused by the fact that the peat media studied here were compressed and finer than the coarse grade defined by Nordic standards (Puustjärvi 1973, 1982a). The water retention of a coarse, uncompressed but compacted, peat growth medium was clearly greater at > –10 kPa (Mannerkoski 1985).

The water retention of the conventionally graded peat was relatively close to that of undisturbed, natural *Sphagnum* bog peat (Päivänen 1973) (Table 8). The standard deviations at different matric potentials were also comparable to those of natural bog peat. The water retention of bog peat at –1500 kPa is, however, somewhat lower than that achieved here. This was probably caused by the presence of more fine particles in the peat growth medium than in undisturbed bog peat. Forest humus layers retained less water at < –1 kPa than the conventionally graded peat growth media did (Heiskanen 1988) (Table 8). The humus material can be considered to be somewhat coarser than the conventional peat grades because of its greater air filled porosity at –1 kPa (θVf–1) (31–50 %). In addition, the humus material is probably more heterogeneous, because the standard deviations in the water retention values were greater than in the peat growth media. Mineral soils and nursery soils based on mineral soils commonly have lower total porosity and retain less water than peat (Päivänen 1973, Westman 1983).

The shrinkage of the peat media at desorption was generally somewhat less than that reported in earlier studies. This may be partly due to the compression that preceded desorption. The volume of relatively dry, loose, low humified *Sphagnum* peat may be up to 25 % lower than when it is wetted (Puustjärvi 1969, 1973, Bunt 1988). Shrinkage of natural *Sphagnum* peat (Db < 0.06) from field moist to oven dry is about 40 % (Päivänen 1982). Shrinkage and compaction tend to decrease the amount of coarse pores and increase that of fine pores, which further affect the water retention and aeration characteristics of peat (Puustjärvi 1973, Langerud 1986, Heiskanen 1990).

It was shown in this study that fine particles (< 1 mm) increased and particles 1–5 mm decreased the water retention characteristics measured. Furthermore, particles < 1 mm decreased and particles 1–5 mm increased the air space at

Table 8. Comparison of bulk density (g cm^{-3}) and water retention characteristics (%) of peat growth media, natural *Sphagnum* bog peat, forest humus layer and open nursery soils.

Reference	Medium	Db	Vf	θ0.1	θ1	θ5	θ10	θ50	θ100	θ1500
	Sphagnum peat media:									
This study	compressed, medium and coarse*	0.07–0.09	95–96	87–93	63–72	36–37	30–31	20–26	19–25	13–16
Puustjärvi 1973	uncompressed, coarse	0.04	97	-	48	23	18	-	-	-
Puustjärvi 1973	uncompressed, medium	0.07	96	-	70	39	29	-	-	-
Mannerkoski 1985	compacted, coarse*	0.07–0.09	-	-	80–90	45–60	35–45	20–25	18–20	-
Heiskanen 1990	compressed, coarse*	0.08–0.09	-	88–93	72–85	-	29–30	-	18–25	-
Päivänen 1973	Natural *Sphagnum* bog peat	0.04–0.07	95–97	92–95	60–91	-	25–49	20–35**	17–30	8–10***
Heiskanen 1988	Forest humus layer	0.09–0.16	91–94	69–83	44–60	-	27–37	-	25–33	14–15
Westman 1983	Nursery soils	0.8–1.4	44–68	-	-	-	21–42	-	-	3–10

*grade specified by manufacturer, ** interpolated, *** extrapolated

–1 kPa. Puustjärvi (1973, 1982b) has also shown that the increase of particles < 1 mm in uncompressed peat growth medium increases water retention at –1 kPa and hence decreases the air space (θVf–1). Particles > 6 mm, on the other hand, clearly increase the air space (Puustjärvi 1973, 1982b). Bulk density of the peat media studied increased water retention more clearly when the matric potential was lower (< –50 kPa). In addition, loss on ignition decreased water retention at –1500 kPa.

The water retention characteristics could be predicted fairly well from the used physical properties of peat, although less accurately at high matric potentials. In addition, the water contents retained within the selected matric potential ranges could be predicted less accurately than at individual matric potentials. The water retention characteristics probably could be predicted more accurately if the heterogeneity of peat material could be measured better. In particular, the particle size fraction classes used in the peat quality standards are rather large and few. The peat particles were found to be concentrated in the finest (< 1 mm) sieving fraction, which is probably due to the fact that peat particles become finer after sieving at the time of manufacture and during transport and handling at nurseries. Hence, the effect of variation in particle size could be better described by also determining fractions finer than 1 mm.

4.2 Sources of variation in water retention characteristics

In general, the water retention characteristics of the conventional peat grades did not differ significantly. However, the peat media of different producers usually differed from each other. The producer and grade interactions were not, in turn, significant, except at –1500 kPa. These observations were due to the fact that the water retention characteristics for the different grades were, on average, about the same for a given producer, but tended to differ between producers. The particle size of the grades also differed between producers. In addition, it is possible that the properties of the peat material were characteristic for each producer due to the specific characteristics of the bogs from which the peat was harvested and due to the manufacturing procedure. The grades were rather similar to each other and were finer than those defined by the Nordic peat quality standards. Peat aggregation or deaggregation and comminution after sieving, compression into containers preceding desorption and shrinkage during desorption probably further decreased the effect of grade on water retention.

Batch clearly affected water retention characteristics at matric potentials < –1 kPa. The variations between peat batches may have been caused by differing peat properties (e.g. composition, humification, compaction) between peat harvesting areas and by variations in peat storage and handling over time. The batch effect was, however, lower than the residual effect within batches, which probably indicates that the peat manufacture within producers and peat handling in nurseries were rather alike over a longer period of time. The clearly greater variation within batches was due to tray effect, because variation within batches due to random measurement error was relatively low. Hence, the clear tray effect was caused mainly by the different properties of the peat before the actual manufacturing process. This may be due to natural variations within peat harvesting areas and changes during storage (e.g. self heating, aggregation, humification).

Although variations within trays were not determined, they may be considerable. To study the actual within tray variations of water retention characteristics, peat sampling from separate containers would be needed. The collection of a large number of sample replications from containers and the physical analyses of such small samples would, however, have been very laborious and difficult or even impossible.

The precision of the water retention measurement was relatively good. The random measurement error was small and had less effect than other sources of variation did. This was due to the relatively great variation in porosity and hence in water retention when the small measurement error did not appear. At –10 kPa, however, the measurement error was significant and was clearly greater than the tray effect. This was probably caused by the relatively low and stable amount of peat pores filled with water around –10 kPa, which further led to low variation in the amounts of water retained. Thus θ5–10 and θ10–50 were relatively small. At desorption, the decrease in the water retention curve around –10 kPa was also gentler (see Mannerkoski 1985). Furthermore, at –10 kPa the standard deviations were relatively small. Therefore, the effect of measurement error, which was relatively less at the other matric potentials, became distinct.

Variations in the water retention measurements may have been due to possible differences in initial degree of saturation, possible variations in sample handling and contact area between samples and ceramic disks, and possibly due to too short desorption times, which may have resulted in some incomplete equilibria of water content at different matric potentials. It is also possible that released peat colloids and precipitates, to some extent, blocked the ceramic disks at desorption altering desorption times and affecting the results. The temperature during measurement in the laboratory may have had an effect, but this was probably relatively small (Päivänen 1973).

Differences in measurement techniques may, on the other hand, markedly affect the results when the water retention characteristics of peat growth media are measured and interpreted. For example, sampling and sample handling during measurements have been shown to influence measurement results (Heiskanen 1990). Compression of peat affects porosity, which in turn affects water retention (Puustjärvi 1969, De Kreij and De Bess 1989). A compression of 10 g cm^{-2} may result in up to a 25 % decrease in volume in loose growth media made of *Sphagnum* peat (Heiskanen 1990). Premoistening and wetting methods may also cause differences in water retention (Puustjärvi 1969). Therefore, the results for determination of water retention characteristics may actually be comparable to those achieved by analogous methods (Heiskanen 1990).

4.3 Implications for seedling growth and irrigation

The significance of water retention in different matric potential ranges on the growth of tree seedlings and their irrigation depends on the phase of growth. If the period of controlled growing in greenhouses and the partly uncontrolled (incl. irrigation) hardening phase at the nursery is the main concern, only the water retention at high matric potentials (wet conditions) is of interest. As far as growth phases after the nursery (which may also include drier conditions) are concerned, lower matric potentials than those in the nursery phase must also be taken into consideration (see Heiskanen 1993a).

In wet conditions in particular, a large amount of air space is needed for sufficient aeration. Usually an air space of 20 % has been regarded as adequate for growth of tree seedlings in the open (Warkentin 1984, see also Heiskanen and

Raitio 1991). But in peat media, even 40–50 % has been considered to be favourable for horticultural plants (Puustjärvi 1973, 1975a, Penningsfeld 1974, see also Heiskanen 1993a). About 40 % may thus be assumed to be the minimum air space in peat media for satisfactory seedling growth. Excluding sheet and chip peat, the peat media studied had less air space at –1 kPa than the minimum requirement. If the matric potential is mostly < –3 kPa during growth, however, it cannot be considered that there was lack of air in any of the peat media studied (see Fig. 1).

The favourable matric potential range for tree seedlings can be considered to be –1 to –50 kPa. The best range in light peat media is probably narrower, within a range of about –1 to –10 kPa (Örlander and Due 1986a,b, Heiskanen 1993a). In the favourable range, the greater the amount of available water, the longer is the period before irrigation is needed. Therefore, it would be reasonable to have the easily available water retention (θ_{1-10}) as high as possible, if sufficient oxygen is available. The easily available water retention was rather high in the conventional peat grades studied, but relatively low in the sheet and chip peat. The less easily available water retention (θ_{10-50}) should also be sufficiently high for adequate water availability when this range of matric potential occurs persistently. Within this matric potential range, seedlings in the peat media studied may dry due to the rather low water retention. The harder available water retention ($\theta_{50-1500}$) can be regarded as a water reserve for seedlings in dry conditions such as after outplanting to a forest site. In the media studied this reserve was probably adequate.

Very unequal distribution of water retention into the matric potential ranges studied may cause inadequate water or oxygen to seedlings. Low water retention between saturation and –1 kPa means small air space and yields low aeration. High water retention within high matric potential ranges (i.e. large air space) may, on the other hand, cause low water retention at low matric potentials. For example, the excessive air space of the sheet peat at –1 kPa (54 %) lessened its ability to retain water at lower matric potentials when there was little (2 %) water available in the range of –10 to –50 kPa. A persistent period of matric potential in this range may thus cause seedlings to dry.

The wider the tolerance for regulating amounts of water and timing of irrigation, the easier it is to adjust irrigation. The greater the easily available amount of water and the less the variation in that amount of water, the wider this tolerance will be. Great variations in the water and aeration characteristics of peat have been found to cause variations in plant growth within a crop (Puustjärvi 1973, 1975a). The average amount of irrigation water needed to increase matric potential from –10 to –1 kPa (θ_{1-10}) was 37 % of the volume in the conventionally graded peat media. In a 10 cm thick layer of peat, this irrigation need corresponds to 37 mm water. The time before –10 kPa is again reached in the peat media and irrigation is needed would be about 10 days, because the average rate of evapotranspiration in greenhouses is 2–4 mm a day (Rikala 1985). However, irrigation may be needed even earlier than when –10 kPa is reached, because the peat surface may become too dry to absorb a sufficient amount of water (see Heiskanen 1993b).

The estimated mean drying time of 10 days from –1 to –10 kPa and the corresponding mean amount of irrigation water, 37 mm, are relatively large, when irrigation is, in principle, fairly easily adjustable. However, the standard deviation of θ_{1-10} within greenhouses was also relatively large, about 10 %-units. This means a corresponding standard deviation of 10 mm in the water content retained in the 10 cm thick peat layer at –1 kPa after application of 37 mm irrigation water at –10 kPa. This relatively high standard deviation may increase the need for more accurate monitoring of irrigation in order to maintain water conditions within the favourable limits in the greenhouse. Large deviations from the average water retention at –1 kPa may hinder aeration in the peat media of seedling trays where the matric potential is higher than –1 kPa due to excessive water. In addition, the risk of hindering aeration may become greater when roots and compaction reduce the amount of coarse pores over time. Thus it may be more reasonable to irrigate less than the whole amount of water at a time and also irrigate more frequently so that aeration limit is not reached in most trays or even in any trays. For example, irrigation at –10 kPa to achieve only –3 to –5 kPa matric potential would not reach the aeration limit in the peat media. The irrigation water needed for the conventionally graded peat media studied here would, for the range –5 to –10 kPa, average about 7 mm with an average irrigation frequency of 3 days at ordinary evaporation rates. Very great variation in water retention within trays may still, however, cause problems in water or oxygen availability to seedlings in separate containers, even though the average irrigation level for trays (within greenhouse) would be determined correctly. Furthermore, different methods of irrigation may have a great effect on the distribution of water into trays and also within trays and containers. In addition, matric potential within an individual container varies vertically, even if the water retention characteristics do not vary (Heiskanen 1993a,b).

Under frequent irrigation in greenhouses and when exposed to rain on hardening fields, aeration may be a more limiting growth factor for seedlings than availability of water. In this case, a large volume of air filled, coarse pores at high matric potentials is needed. Sufficient volume of coarse pores (θV_{f-1}) is especially needed also during growing periods longer than one year, because peat tends to compact and its air space be reduced over time (Puustjärvi 1975b, Langerud 1986, see also Mannerkoski 1982). In this respect, due to its coarse porosity, sheet peat probably best provides sufficient aeration. If irrigation is infrequent, seedlings are not exposed to free rain and the growing period is not longer than one year, a large air space at high matric potentials is not a main consideration. Instead, a large amount of available water in the growth medium, as indeed is for the conventionally graded peat media studied, is more important for seedling growth. The actual methods of irrigation and growth conditions under which seedlings are grown in individual containers are, however, the criteria which finally determine how the properties of media affect growth. Values for those water retention characteristics which are significant for seedling growth and irrigation should thus, in the intrest of accuracy, be determined for each condition separately.

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Total of 44 references

Appendix 1. Correlation matrix of the measured variables of the conventionally graded peat. Batch means were used as independent observations (n = 20). In the case of bivariate normality, the smallest significant coefficient is 0.44 (p < 0.05).

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1 F < 1	1.00																									
2 F1–5	–0.96	1.00																								
3 F5–10	–0.34	0.12	1.00																							
4 F10–20	–0.46	0.23	0.44	1.00																						
5 F > 20	–0.13	0.02	0.08	0.38	1.00																					
6 Il	–0.10	0.04	–0.01	0.34	0.31	1.00																				
7 Ks	0.38	–0.43	0.16	–0.20	0.26	0.22	1.00																			
8 Dp	–0.34	0.23	0.62	0.17	0.09	–0.30	–0.11	1.00																		
9 Db	0.65	–0.64	–0.38	–0.08	0.03	–0.14	0.02	–0.16	1.00																	
10 Vf	–0.63	0.59	0.50	0.07	0.04	0.01	0.02	0.41	–0.95	1.00																
11 θ0.1	0.61	–0.57	–0.34	–0.28	0.09	0.02	0.51	–0.36	0.33	–0.32	1.00															
12 θ1	0.48	–0.52	–0.14	–0.01	0.26	0.11	0.45	–0.28	0.41	–0.41	0.62	1.00														
13 θ5	0.37	–0.51	0.26	0.18	0.35	0.01	0.27	0.21	0.33	–0.21	0.36	0.61	1.00													
14 θ10	0.49	–0.61	0.22	0.08	0.37	–0.01	0.42	0.15	0.31	–0.18	0.52	0.61	0.96	1.00												
15 θ50	0.80	–0.78	–0.30	–0.30	0.14	0.03	0.51	–0.32	0.75	–0.73	0.72	0.71	0.47	0.56	1.00											
16 θ100	0.80	–0.77	–0.33	–0.32	0.13	–0.02	0.45	–0.33	0.77	–0.76	0.70	0.68	0.46	0.54	0.99	1.00										
17 θ1500	0.60	–0.59	–0.24	–0.15	–0.10	–0.43	–0.11	–0.11	0.78	–0.75	0.09	0.28	0.37	0.34	0.55	0.61	1.00									
18 θVf–1	–0.52	0.55	0.18	0.01	–0.24	–0.11	–0.43	0.30	–0.47	0.47	–0.62	–0.99	–0.60	–0.60	–0.74	–0.72	–0.33	1.00								
19 θ1–10	0.41	–0.42	–0.23	–0.03	0.18	0.13	0.39	–0.37	0.38	–0.41	0.56	0.97	0.41	0.40	0.65	0.62	0.22	–0.97	1.00							
20 θ10–50	–0.59	0.48	0.53	0.42	0.11	–0.05	–0.30	0.50	–0.67	0.73	–0.47	–0.40	0.15	0.08	–0.78	–0.79	–0.41	0.44	–0.48	1.00						
21 θ50–1500	0.44	–0.43	–0.16	–0.23	0.25	0.39	0.69	–0.29	0.24	–0.23	0.77	0.60	0.24	0.38	0.72	0.67	–0.18	–0.60	0.58	–0.59	1.00					
22 V1	0.48	–0.53	0.13	–0.16	0.15	–0.01	0.31	0.09	0.43	–0.36	0.45	0.60	0.53	0.54	0.71	0.70	0.42	–0.60	0.52	–0.44	0.48	1.00				
23 V5	0.42	–0.48	0.29	–0.22	–0.15	–0.29	0.23	0.30	0.56	–0.42	0.14	0.20	0.26	0.29	0.59	0.60	0.54	–0.22	0.14	–0.50	0.25	0.68	1.00			
24 V10	0.56	–0.61	0.11	–0.20	0.17	0.01	0.39	–0.06	0.56	–0.50	0.43	0.46	0.51	0.56	0.76	0.77	0.48	–0.49	0.37	–0.50	0.50	0.75	0.72	1.00		
25 V50	0.54	–0.58	0.16	–0.29	0.07	–0.27	0.30	0.12	0.62	–0.51	0.32	0.41	0.41	0.44	0.72	0.73	0.57	–0.44	0.34	–0.53	0.37	0.81	0.87	0.84	1.00	
26 V100	0.63	–0.68	0.17	–0.26	–0.10	–0.19	0.51	0.06	0.52	–0.43	0.51	0.42	0.38	0.51	0.76	0.76	0.45	–0.44	0.33	–0.53	0.53	0.63	0.83	0.79	0.78	1.00

Appendix 2. General means (μ) and fixed effects (as deviations from the general mean) and standard deviations (Sd) of random effects of water retention characteristics (from Model 4).

Variable	μ	Cell, ij	α_i	β_j	γ_{ij}	$Sd(d_{(ij)k})$	$Sd(e_{(ijk)l})$
Vf	95.2	11	–0.4	–0.1	–0.1	0.2	0.5
		12	–0.4	0.1	0.1	0.2	0.5
		21	0.4	–0.1	0.1	0.2	0.5
		22	0.4	0.1	–0.1	0.2	0.5
θ0.1	90.2	11	1.9	–1.2	0.3	1.4	3.7
		12	1.9	1.2	–0.3	1.4	3.7
		21	–1.9	–1.2	–0.3	1.4	3.7
		22	–1.9	1.2	0.3	1.4	3.7
θ1	67.2	11	3.8	–0.4	–0.3	1.8	10.7
		12	3.8	0.4	0.3	1.8	10.7
		21	–3.8	–0.4	0.3	1.8	10.7
		22	–3.8	0.4	–0.3	1.8	10.7
θ5	36.5	11	0.3	0.1	0.04	1.9	2.5
		12	0.3	–0.1	–0.04	1.9	2.5
		21	–0.3	0.1	–0.04	1.9	2.5
		22	–0.3	–0.1	0.04	1.9	2.5
θ10	30.5	11	0.3	–0.3	0.05	1.5	1.7
		12	0.3	0.3	–0.05	1.5	1.7
		21	–0.3	–0.3	–0.05	1.5	1.7
		22	–0.3	0.3	0.05	1.5	1.7
θ50	22.8	11	2.2	–0.6	0.1	1.1	1.6
		12	2.2	0.6	–0.1	1.1	1.6
		21	–2.2	–0.6	–0.1	1.1	1.6
		22	–2.2	0.6	0.1	1.1	1.6
θ100	22.2	11	2.2	–0.5	0.2	1.2	1.5
		12	2.2	0.5	–0.2	1.2	1.5
		21	–2.2	–0.5	–0.2	1.2	1.5
		22	–2.2	0.5	0.2	1.2	1.5
θ1500	14.7	11	0.7	0.2	0.8	1.3	2.0
		12	0.7	–0.2	–0.8	1.3	2.0
		21	–0.7	0.2	–0.8	1.3	2.0
		22	–0.7	–0.2	0.8	1.3	2.0

Appendix 3. General means (μ) and fixed effects (as deviations from the general mean) and standard deviations (Sd) of random effects of water retention characteristics within selected matric potential ranges (from Model 4).

Variable	μ	Cell, ij	α_i	β_j	γ_{ij}	$Sd(d_{(ij)k})$	$Sd(e_{(ijk)l})$
θVf–1	28.0	11	–4.2	0.3	0.2	1.7	10.7
		12	–4.2	–0.3	–0.2	1.7	10.7
		21	4.2	0.3	–0.2	1.7	10.7
		22	4.2	–0.3	0.2	1.7	10.7
θ1–10	36.7	11	3.5	–0.1	–0.3	≈0	10.2
		12	3.5	0.1	0.3	≈0	10.2
		21	–3.5	–0.1	0.3	≈0	10.2
		22	–3.5	0.1	–0.3	≈0	10.2
θ10–50	7.8	11	–1.9	0.3	–0.02	0.8	1.7
		12	–1.9	–0.3	0.02	0.8	1.7
		21	1.9	0.3	0.02	0.8	1.7
		22	1.9	–0.3	–0.02	0.8	1.7
θ50–1500	8.1	11	1.5	–0.8	–0.7	0.5	2.4
		12	1.5	0.8	0.7	0.5	2.4
		21	–1.5	–0.8	0.7	0.5	2.4
		22	–1.5	0.8	–0.7	0.5	2.4